

Hello from the Other Side: SSH over Robust Cache Covert Channels in the Cloud

Clémentine Maurice, Manuel Weber, Michael Schwarz, Lukas Giner, Daniel Gruss, Carlo Alberto Boano, Stefan Mangard, Kay Römer
Graz University of Technology

February 2017 — NDSS 2017

Outline

- cache covert channels
- how do we get a covert channel working in the **cloud**?
- how do we get a covert channel working in a **noisy environment**?
- what are the **applications** of such covert channel?

CPU cache

- main memory is slow compared to the CPU

CPU cache

- main memory is slow compared to the CPU
- caches buffer frequently used data

CPU cache

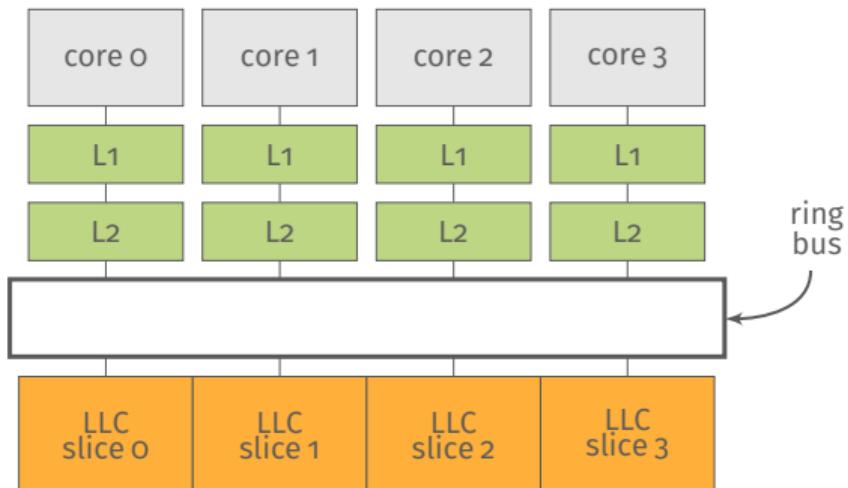
- main memory is slow compared to the CPU
- caches buffer frequently used data
- every data access goes through the cache

CPU cache

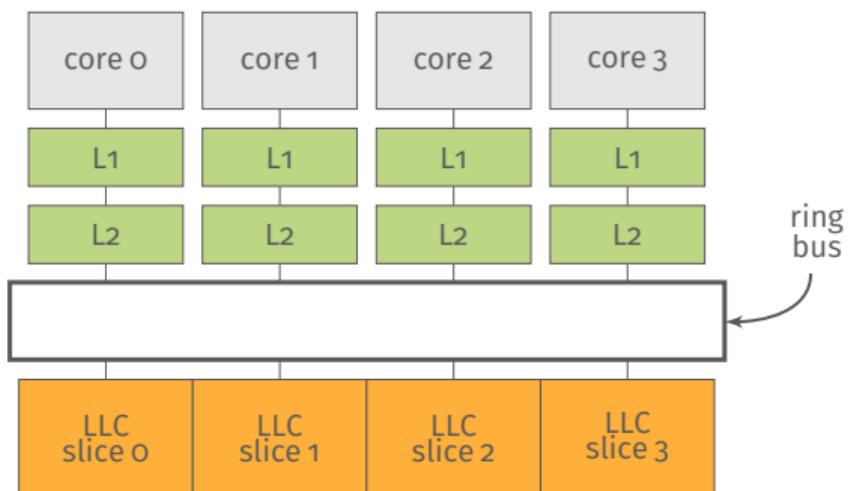
- main memory is slow compared to the CPU
- caches buffer frequently used data
- every data access goes through the cache
- caches are transparent to the OS and the software

Caches on Intel CPUs

- L1 and L2 are private

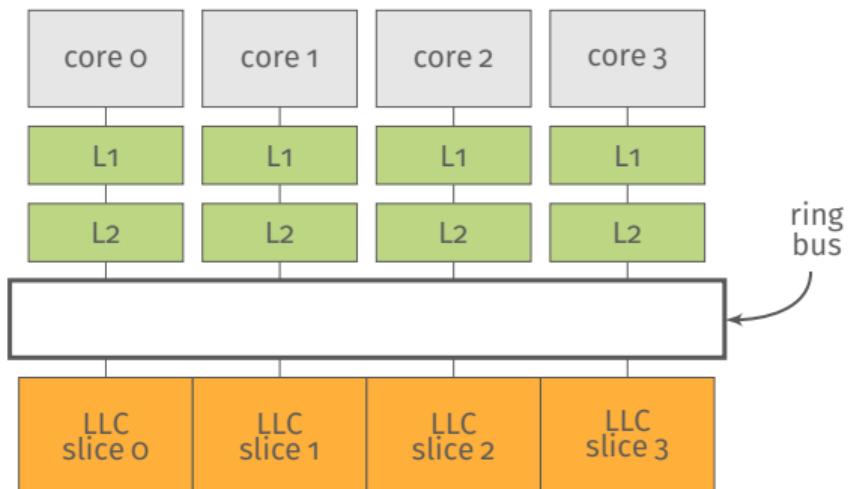


Caches on Intel CPUs



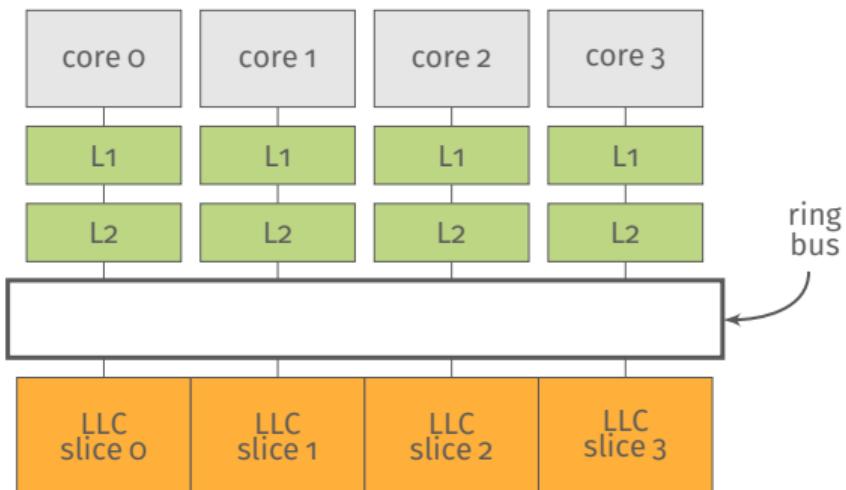
- L1 and L2 are private
- last-level cache

Caches on Intel CPUs



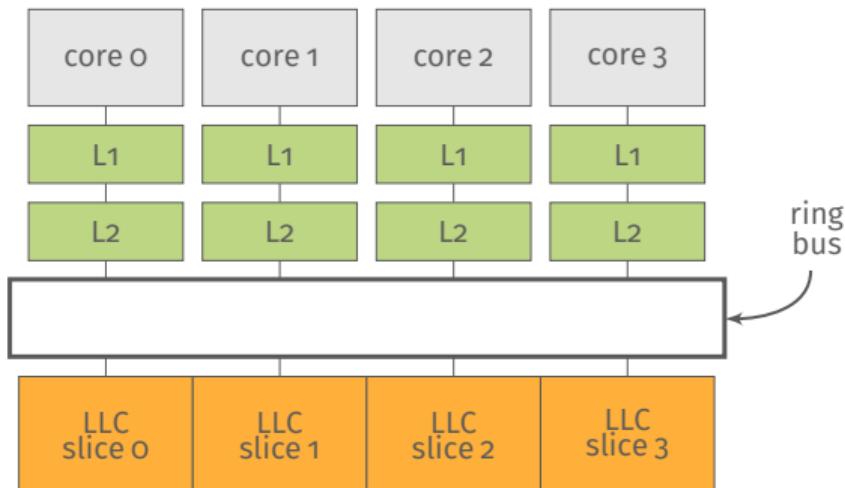
- L1 and L2 are private
- last-level cache
 - divided in **slices**

Caches on Intel CPUs



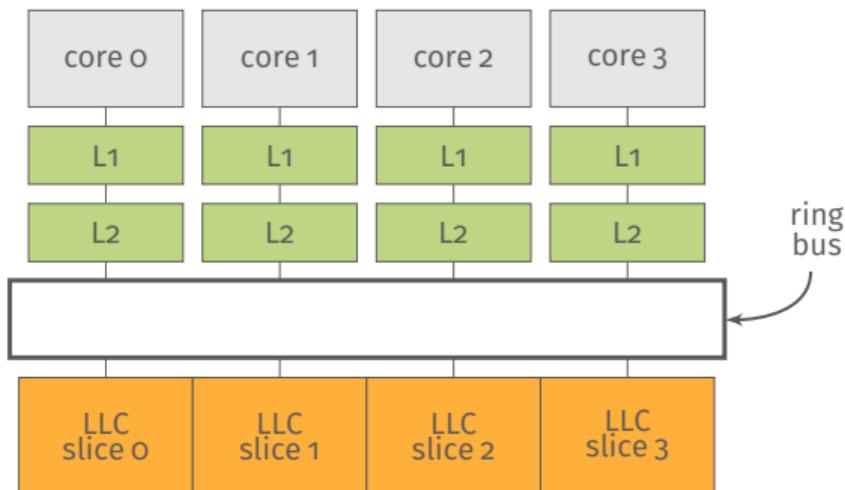
- L1 and L2 are private
- last-level cache
 - divided in **slices**
 - **shared** across cores

Caches on Intel CPUs



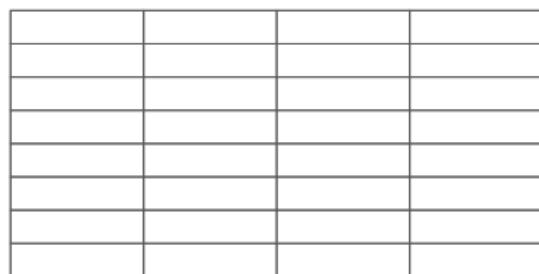
- L1 and L2 are private
- last-level cache
 - divided in **slices**
 - **shared** across cores
 - **inclusive**

Caches on Intel CPUs



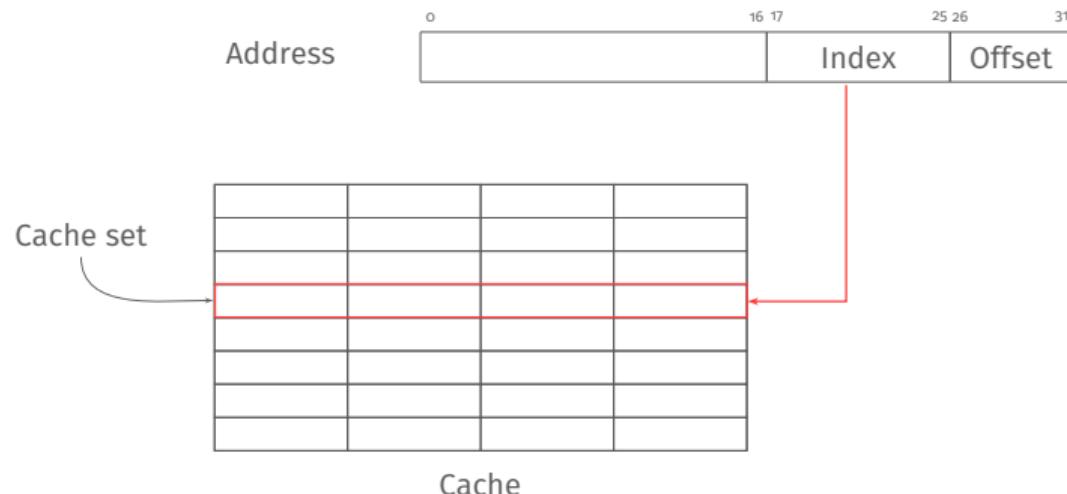
- L1 and L2 are private
- last-level cache
 - divided in **slices**
 - **shared** across cores
 - **inclusive**
 - hash function maps a physical address to a slice

Set-associative caches



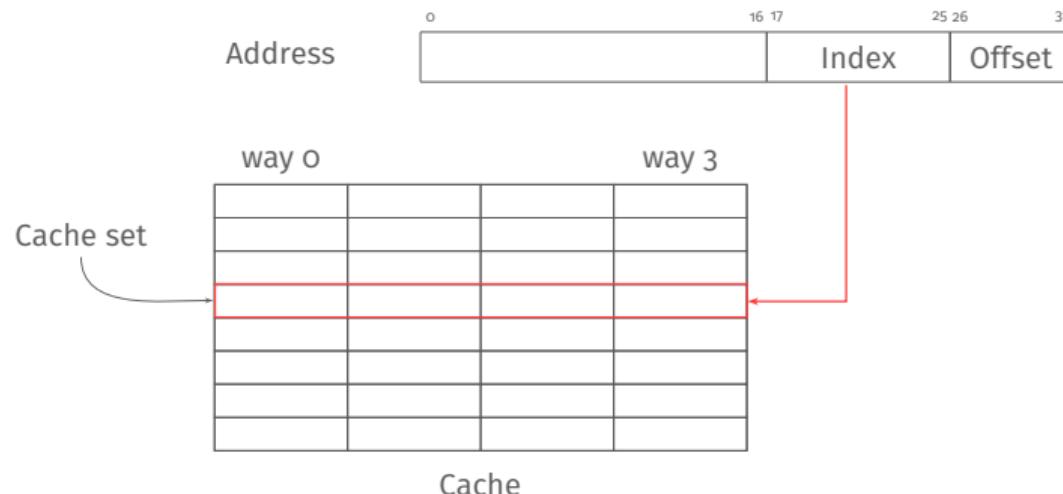
Cache

Set-associative caches



Data loaded in a specific **set** depending on its address

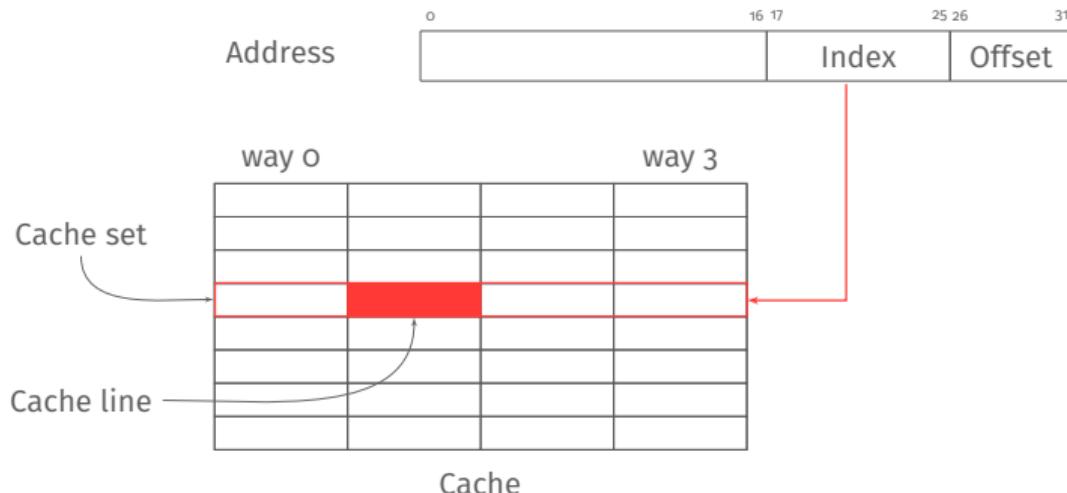
Set-associative caches



Data loaded in a specific **set** depending on its address

Several **ways** per set

Set-associative caches

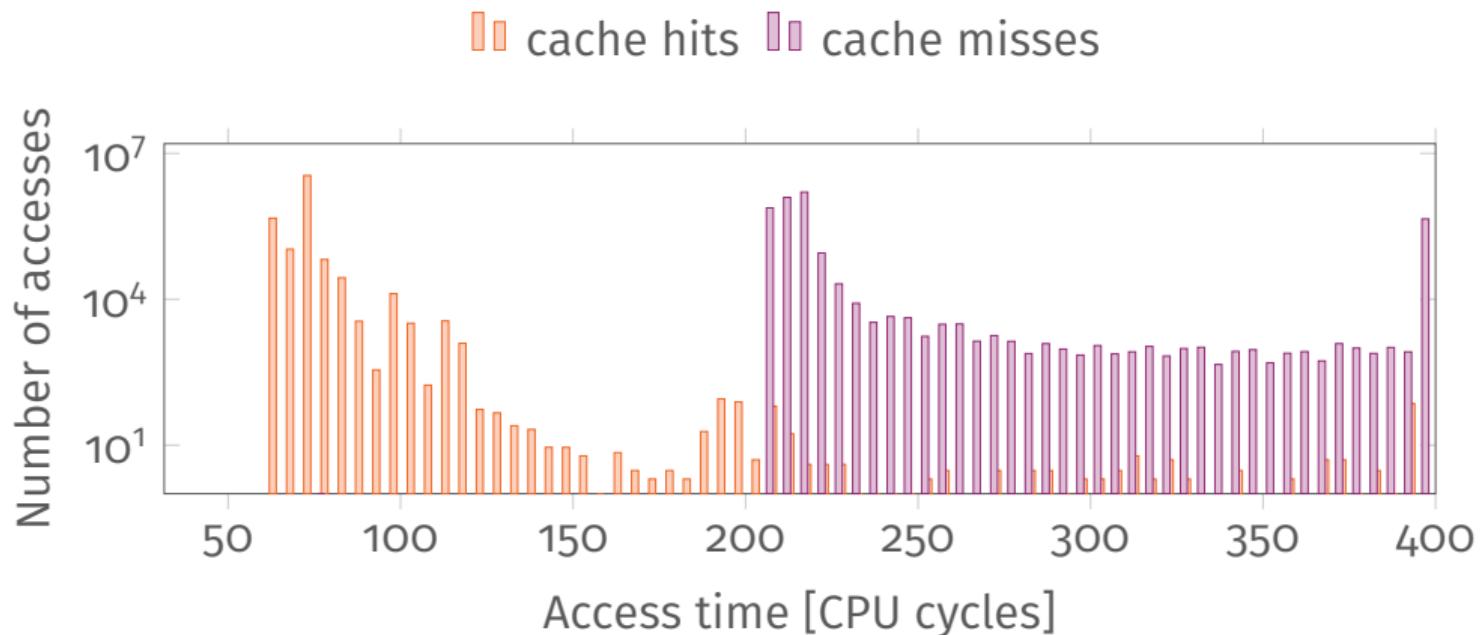


Data loaded in a specific **set** depending on its address

Several **ways** per set

Cache line loaded in a specific way depending on the replacement policy

Timing differences



Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses

Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses
- covert channel: two processes **communicating** with each other
 - **not allowed** to do so, e.g., across VMs

Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses
- covert channel: two processes **communicating** with each other
 - **not allowed** to do so, e.g., across VMs
- literature: stops working with **noise** on the machine

Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses
- covert channel: two processes **communicating** with each other
 - **not allowed** to do so, e.g., across VMs
- literature: stops working with **noise** on the machine
- solution? “Just use error-correcting codes”

Prime+Probe

- attacker knows which **cache set** the victim **accessed**, not the content

Prime+Probe

- attacker knows which **cache set** the victim **accessed**, not the content
- works **across CPU cores** as the last-level cache is shared

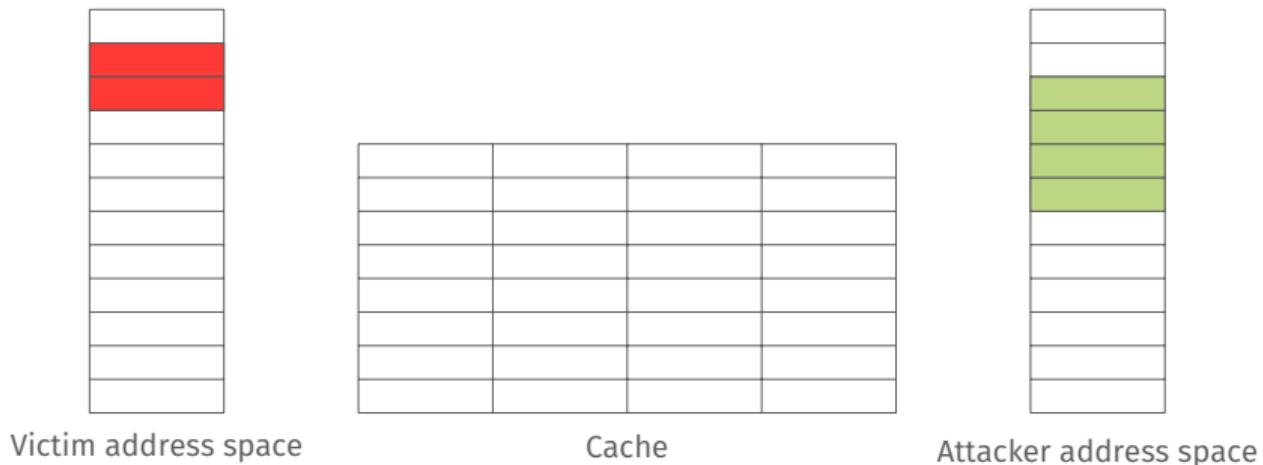
Prime+Probe

- attacker knows which **cache set** the victim **accessed**, not the content
- works **across CPU cores** as the last-level cache is shared
- does not need shared memory, e.g., memory de-duplication

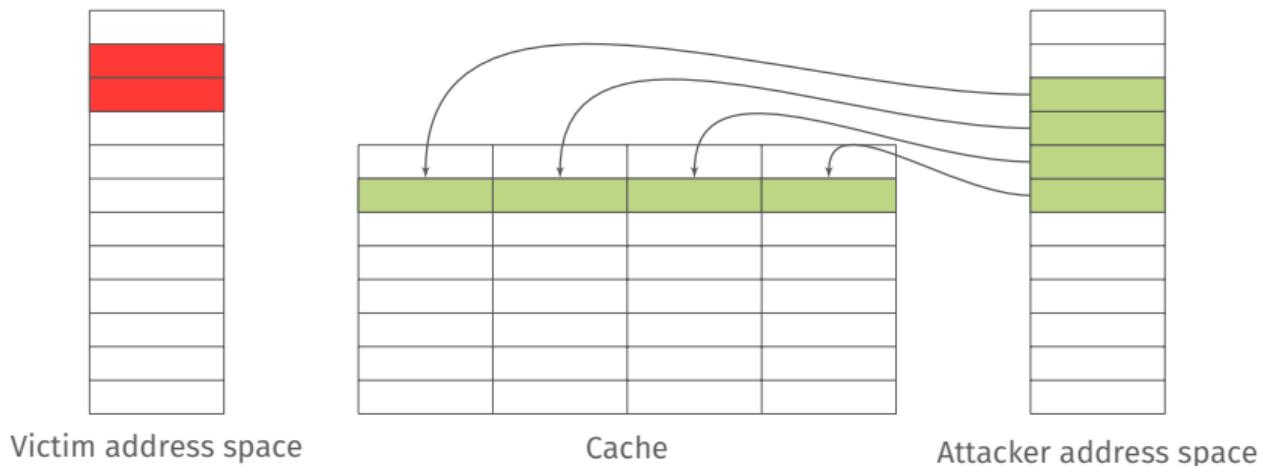
Prime+Probe

- attacker knows which **cache set** the victim **accessed**, not the content
 - works **across CPU cores** as the last-level cache is shared
 - does not need shared memory, e.g., memory de-deduplication
- works **across VM in the cloud**, e.g., on Amazon EC2

Prime+Probe

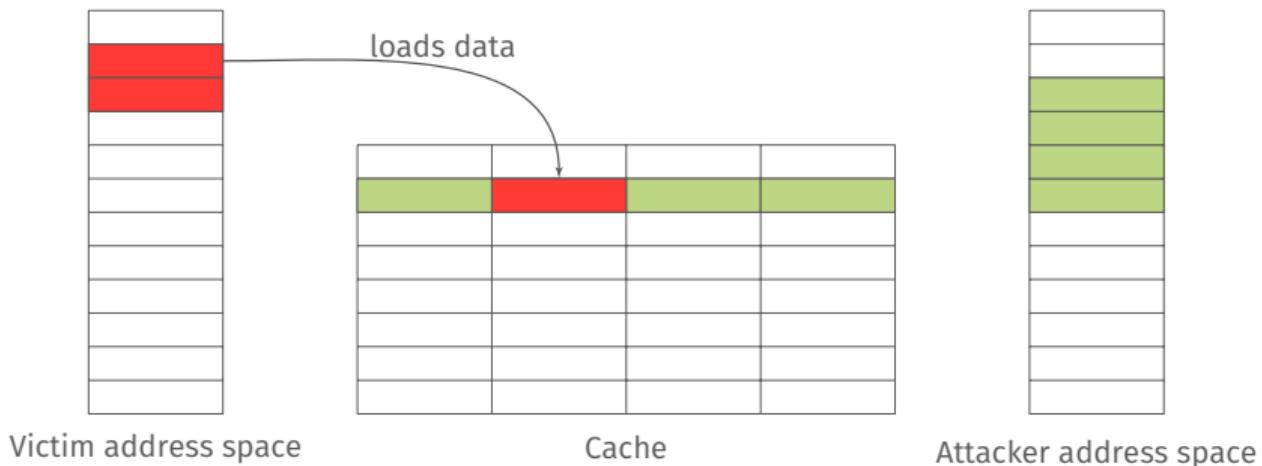


Prime+Probe



Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

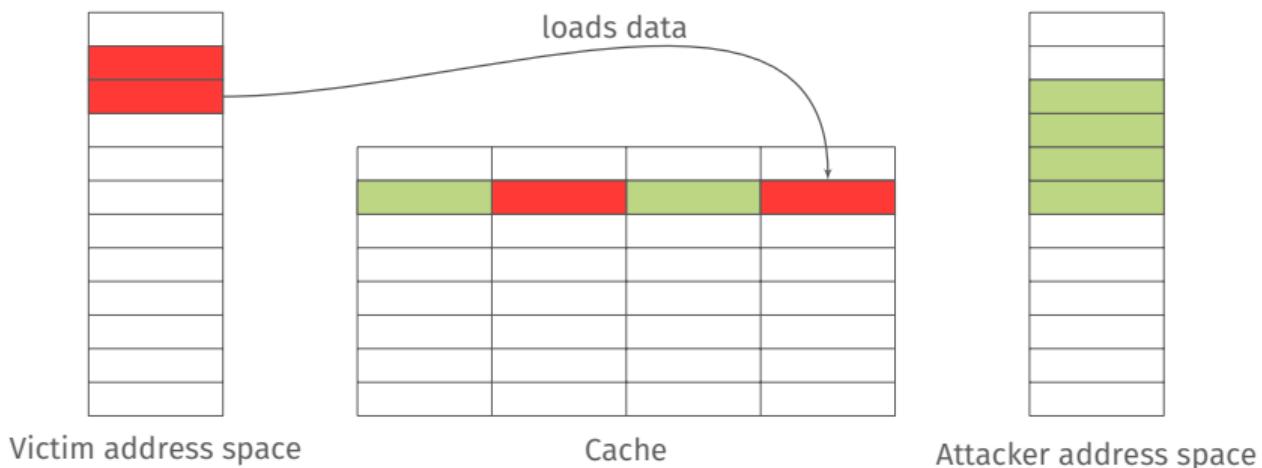
Prime+Probe



Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

Step 2: Victim evicts cache lines while running

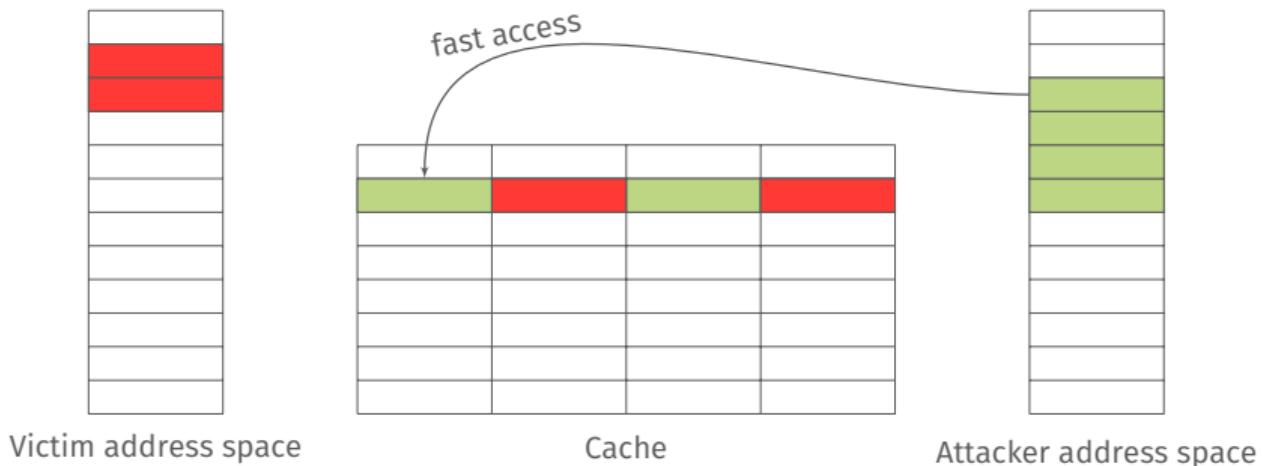
Prime+Probe



Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

Step 2: Victim evicts cache lines while running

Prime+Probe

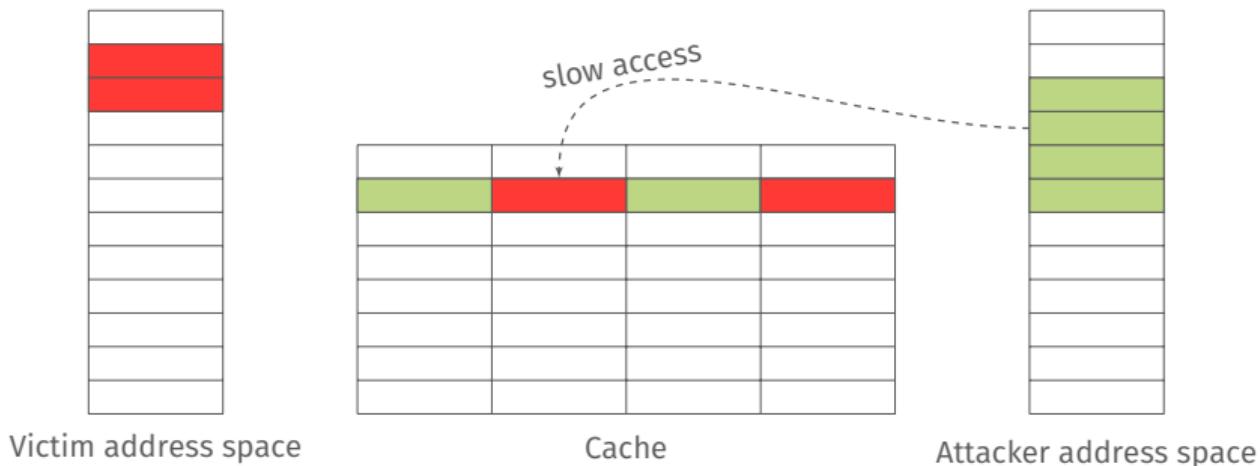


Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

Step 2: Victim evicts cache lines while running

Step 3: Attacker **probes** data to determine if set has been accessed

Prime+Probe



Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

Step 2: Victim evicts cache lines while running

Step 3: Attacker **probes** data to determine if set has been accessed

Why can't we just use error correcting codes?

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	0	1	1	0
---	---	---	---	---	---



(a) Transmission without errors

Why can't we just use error correcting codes?

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	0	1	1	0
---	---	---	---	---	---



(a) Transmission without errors

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	1	0	1	1	0
---	---	---	---	---	---



(b) Noise: **substitution** error

Why can't we just use error correcting codes?

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	0	1	1	0
---	---	---	---	---	---



(a) Transmission without errors

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	1	0	1	1	0
---	---	---	---	---	---



(b) Noise: **substitution** error

Sender

1	0	██████	0	1	1	0
---	---	--------	---	---	---	---



Receiver

1	0	0	0	0	0	1	1	0
---	---	---	---	---	---	---	---	---



(c) Sender descheduled: **insertions**

Why can't we just use error correcting codes?

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	0	1	1	0
---	---	---	---	---	---



(a) Transmission without errors

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	1	0	1	1	0
---	---	---	---	---	---



(b) Noise: **substitution** error

Sender

1	0	██████	0	1	1	0
---	---	--------	---	---	---	---



Receiver

1	0	0	0	0	0	1	1	0
---	---	---	---	---	---	---	---	---



(c) Sender descheduled: **insertions**

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	██████	0
---	---	--------	---



(d) Receiver descheduled: **deletions**

Our robust covert channel

- **physical** layer:
 - transmits words as a sequence of '0's and '1's
 - deals with synchronization errors
- **data-link** layer:
 - divides data to transmit into packets
 - corrects the remaining errors

Physical layer: Sending '0's and '1's

- sender and receiver agree on one set

Physical layer: Sending '0's and '1's

- sender and receiver agree on one set
- receiver probes the set continuously

Physical layer: Sending '0's and '1's

- sender and receiver agree on one set
- receiver probes the set continuously
- sender **transmits '0'** doing nothing
→ lines of the receiver still in cache → **fast access**

Physical layer: Sending '0's and '1's

- sender and receiver agree on one set
- receiver probes the set continuously
- sender **transmits '0'** doing nothing
 - lines of the receiver still in cache → **fast access**
- sender **transmits '1'** accessing addresses in the set
 - evicts lines of the receiver → **slow access**

Eviction set generation

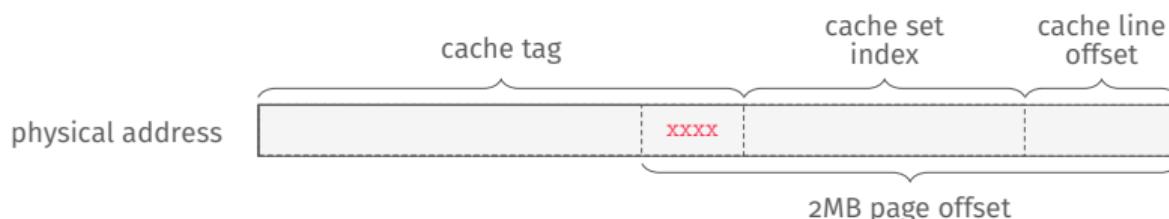
- need a set of addresses in the **same cache set** and **same slice**

Eviction set generation

- need a set of addresses in the **same cache set** and **same slice**
- problem: slice number depends on all bits of the physical address

Eviction set generation

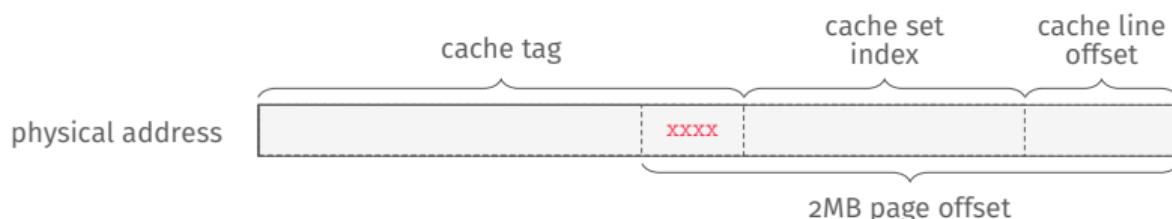
- need a set of addresses in the **same cache set** and **same slice**
- problem: slice number depends on all bits of the physical address



- we can build a set of addresses in the **same cache set** and **same slice**

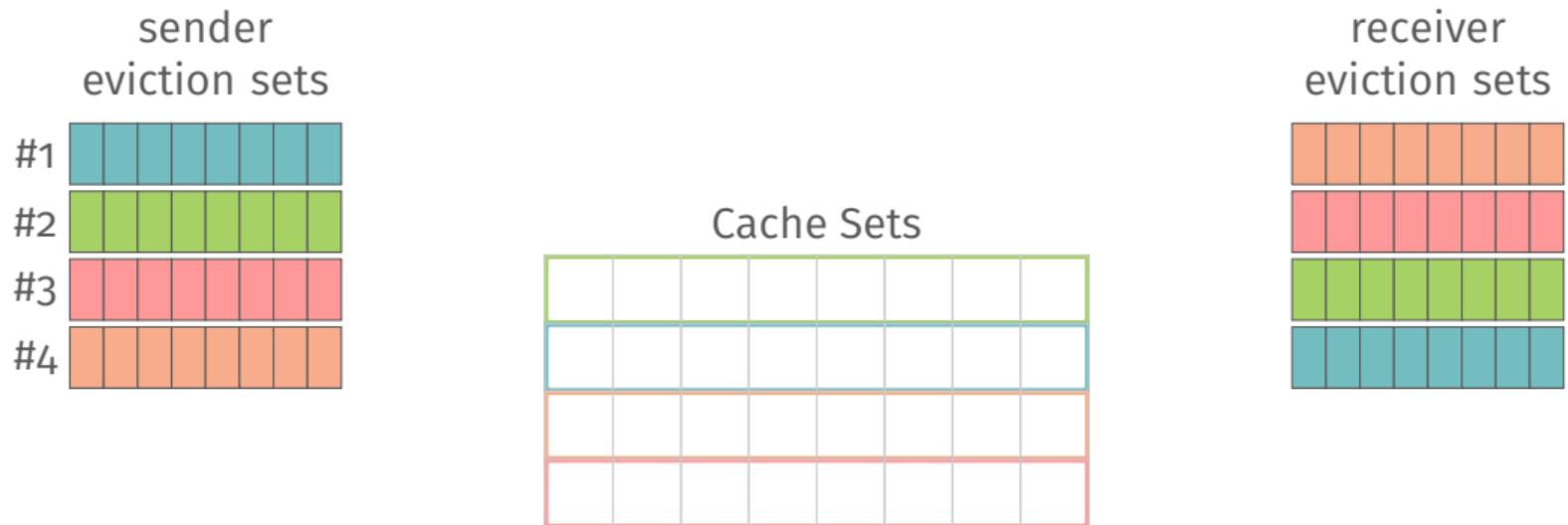
Eviction set generation

- need a set of addresses in the **same cache set** and **same slice**
- problem: slice number depends on all bits of the physical address

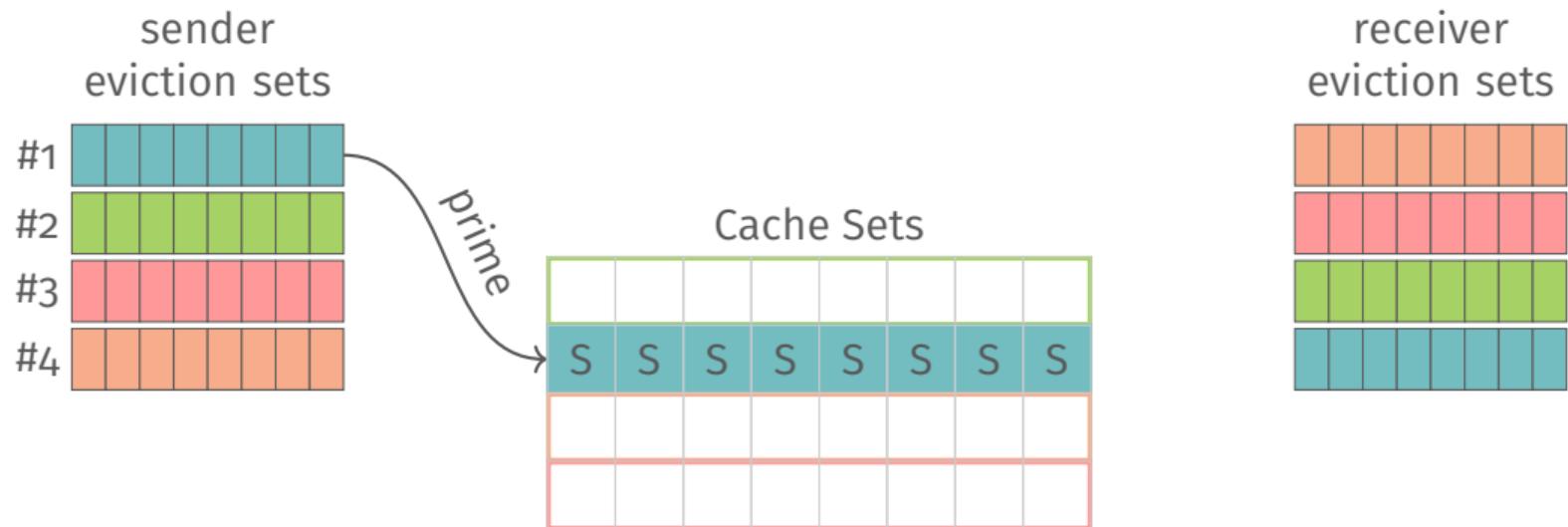


- we can build a set of addresses in the **same cache set** and **same slice**
- without knowing **which slice**

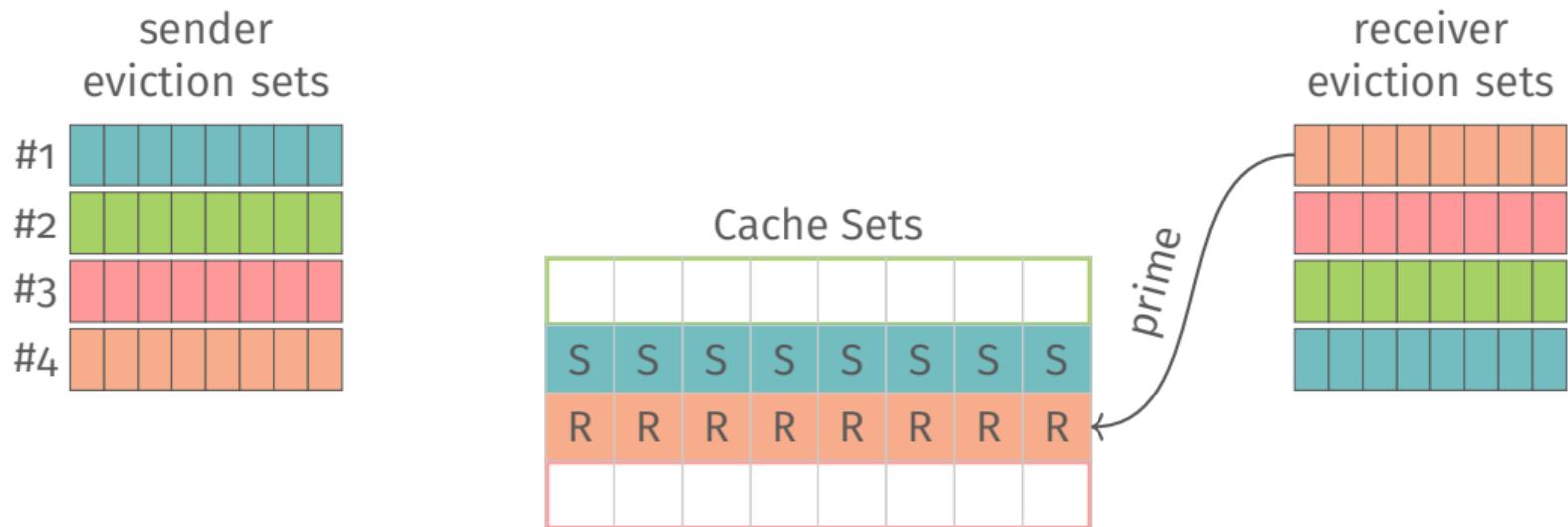
Jamming agreement



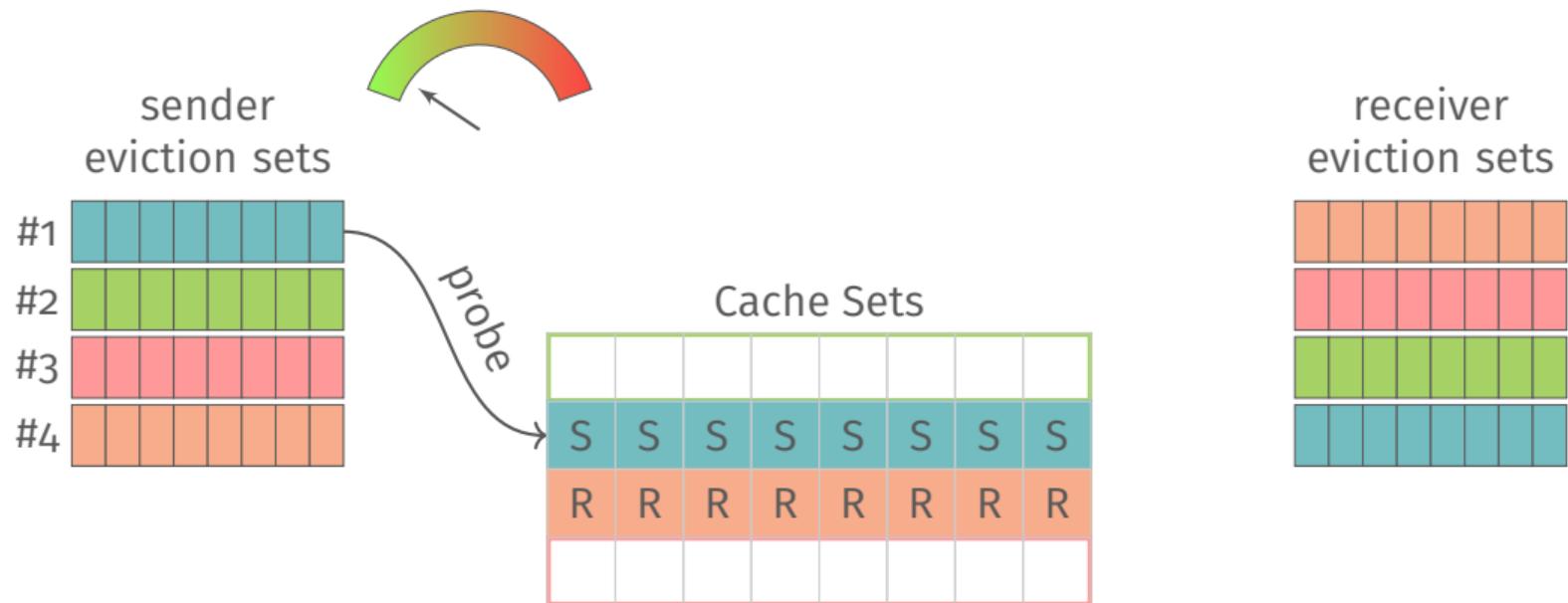
Jamming agreement



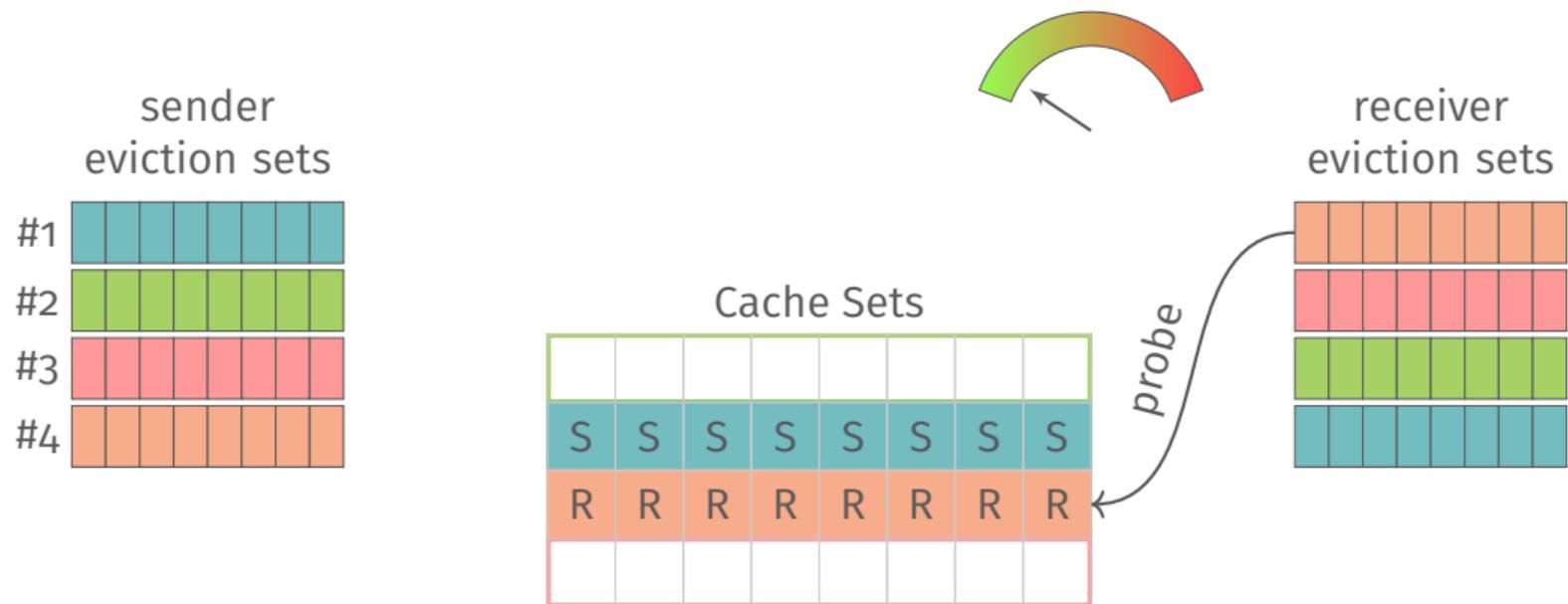
Jamming agreement



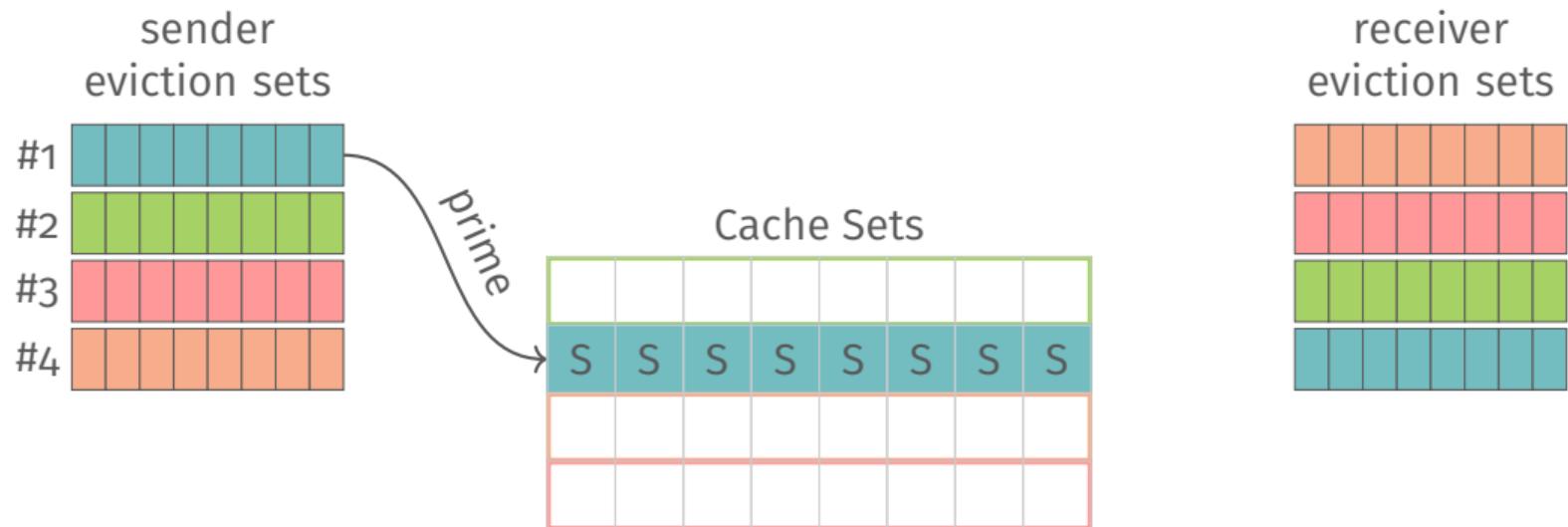
Jamming agreement



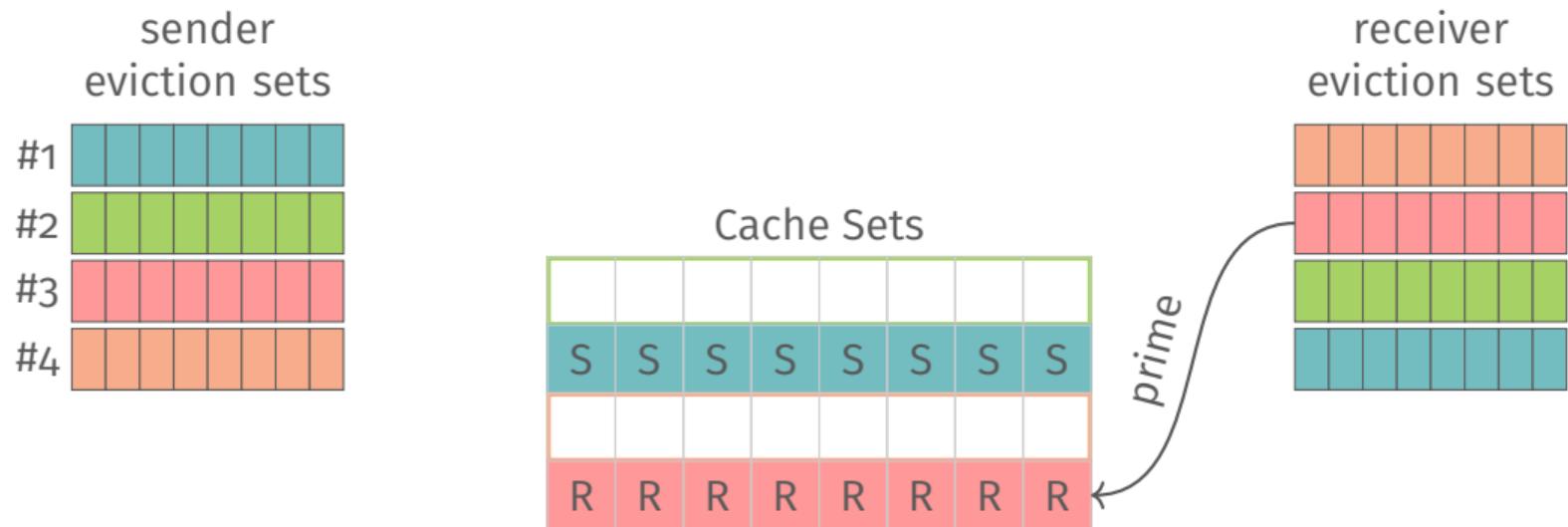
Jamming agreement



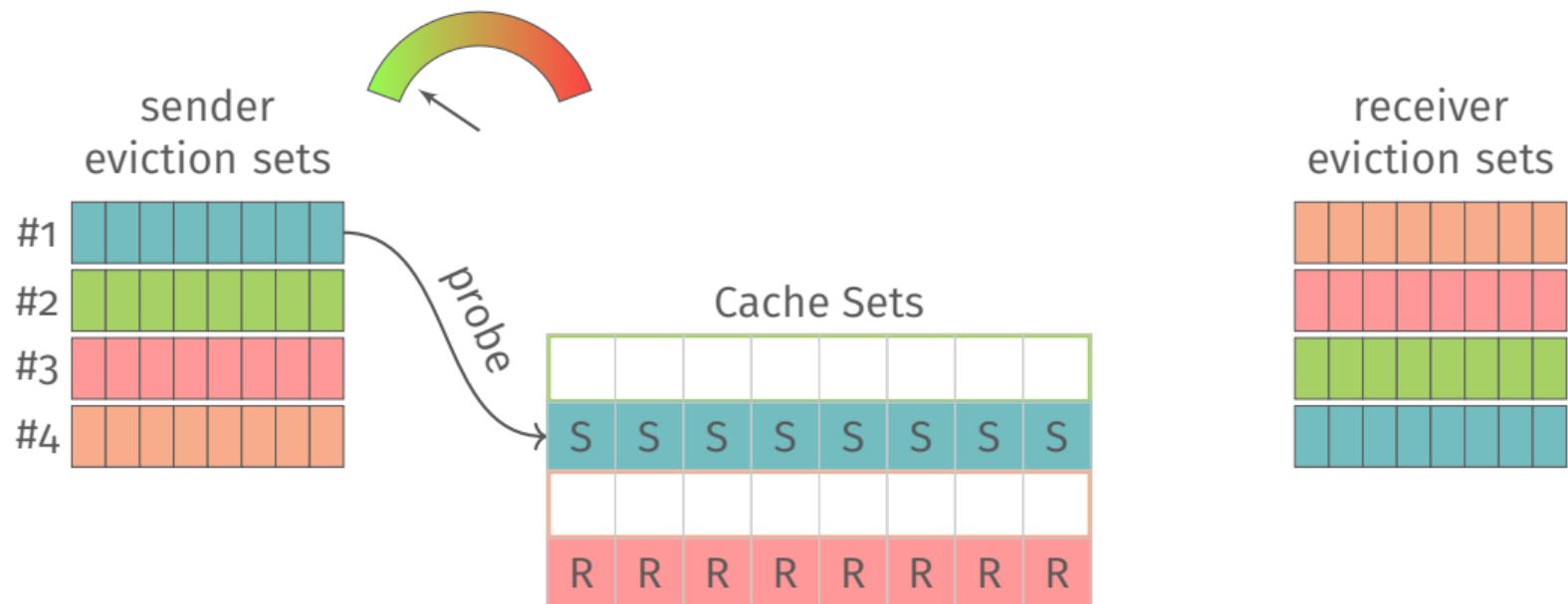
Jamming agreement



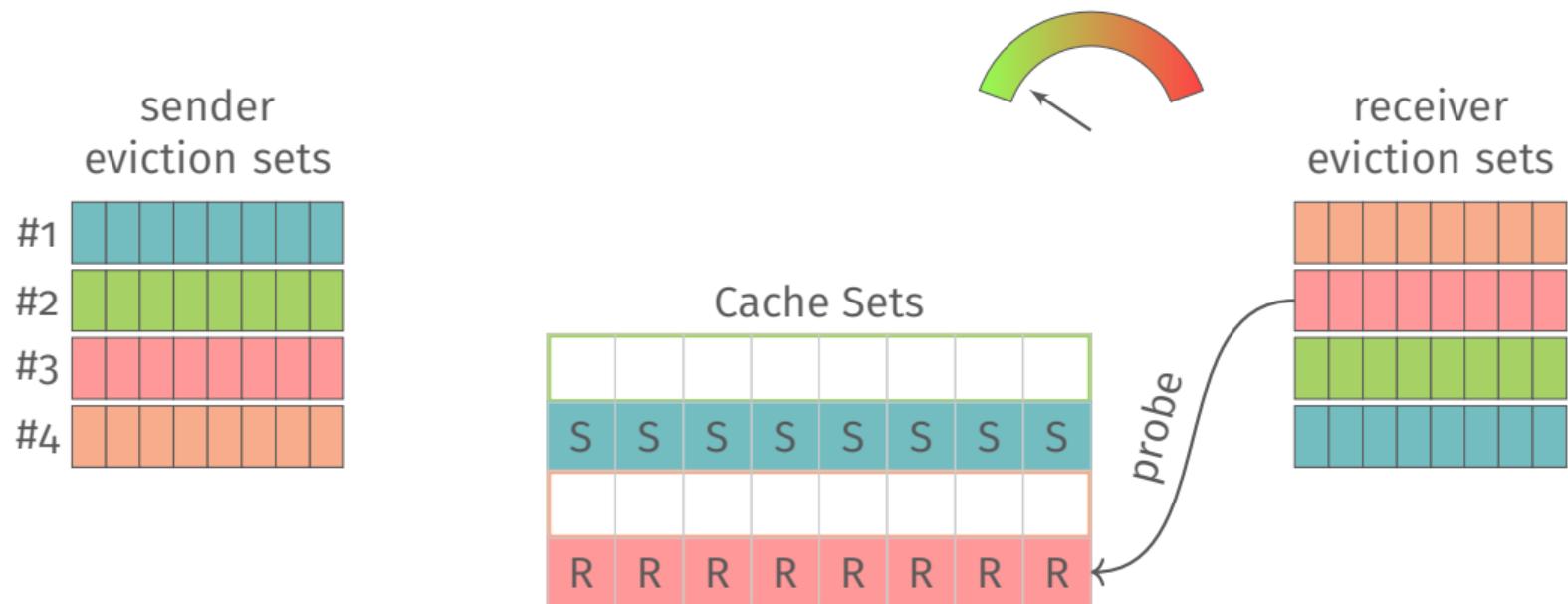
Jamming agreement



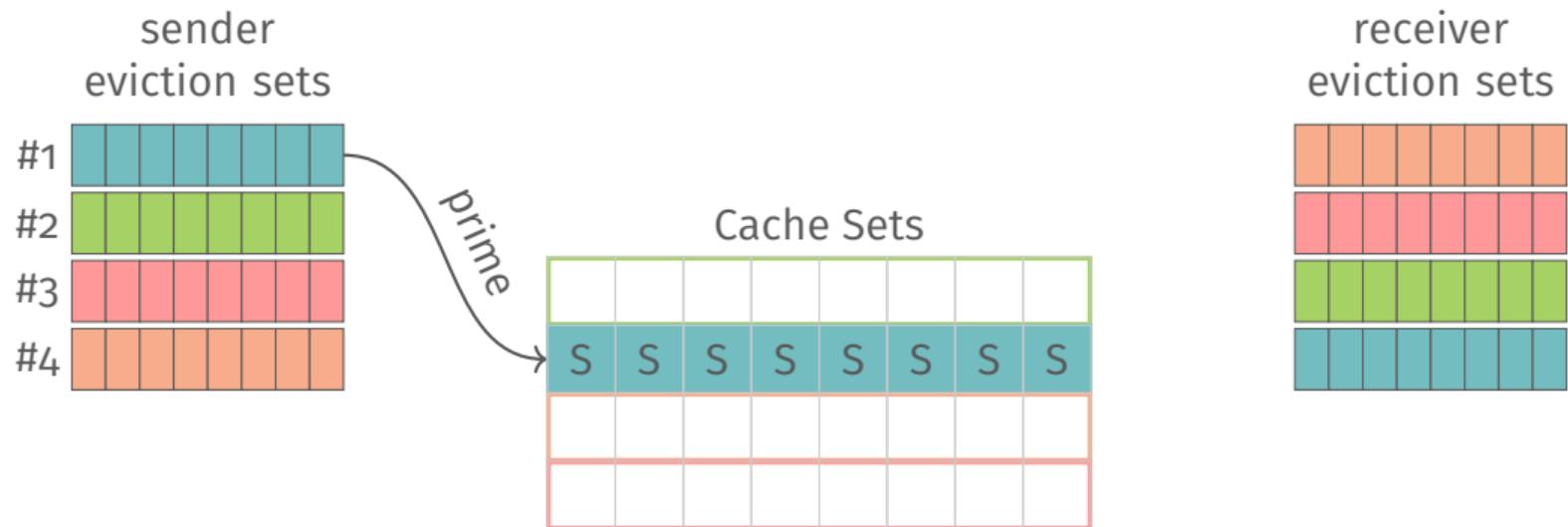
Jamming agreement



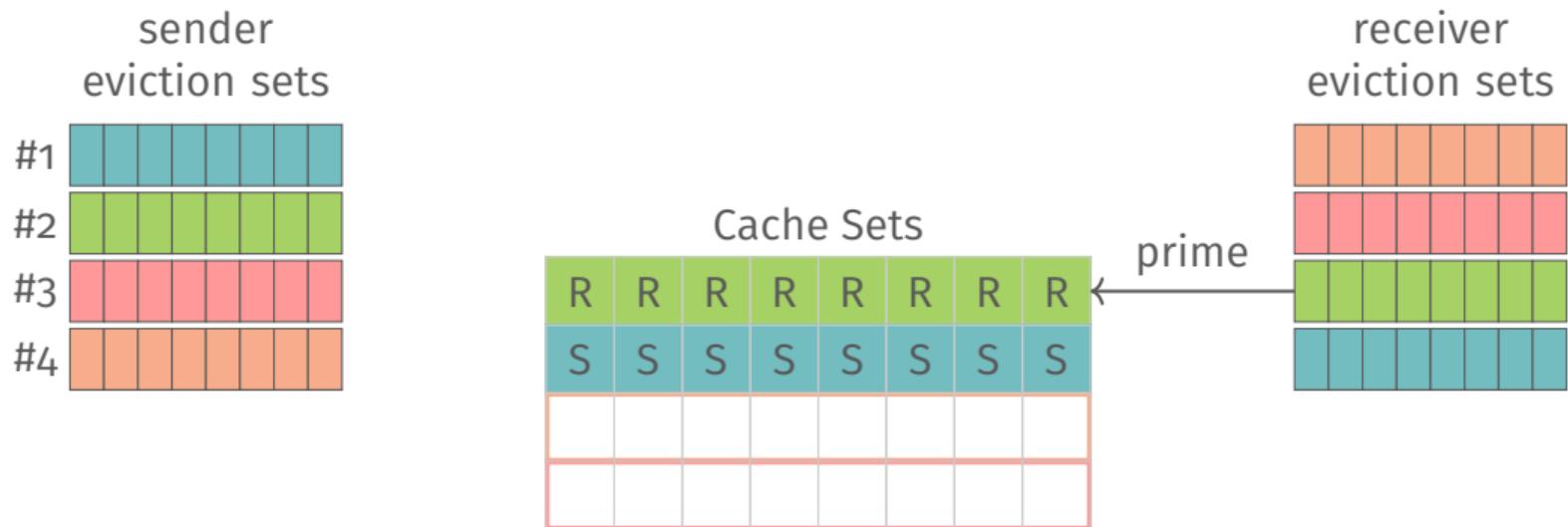
Jamming agreement



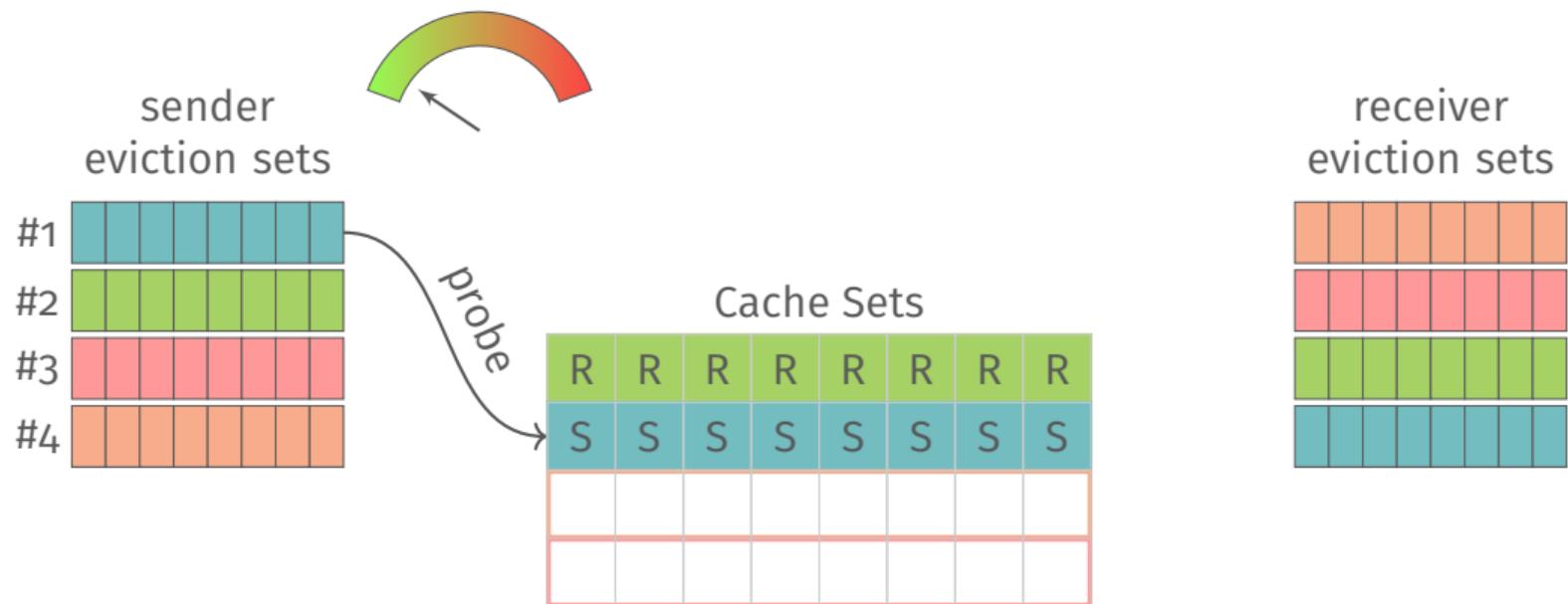
Jamming agreement



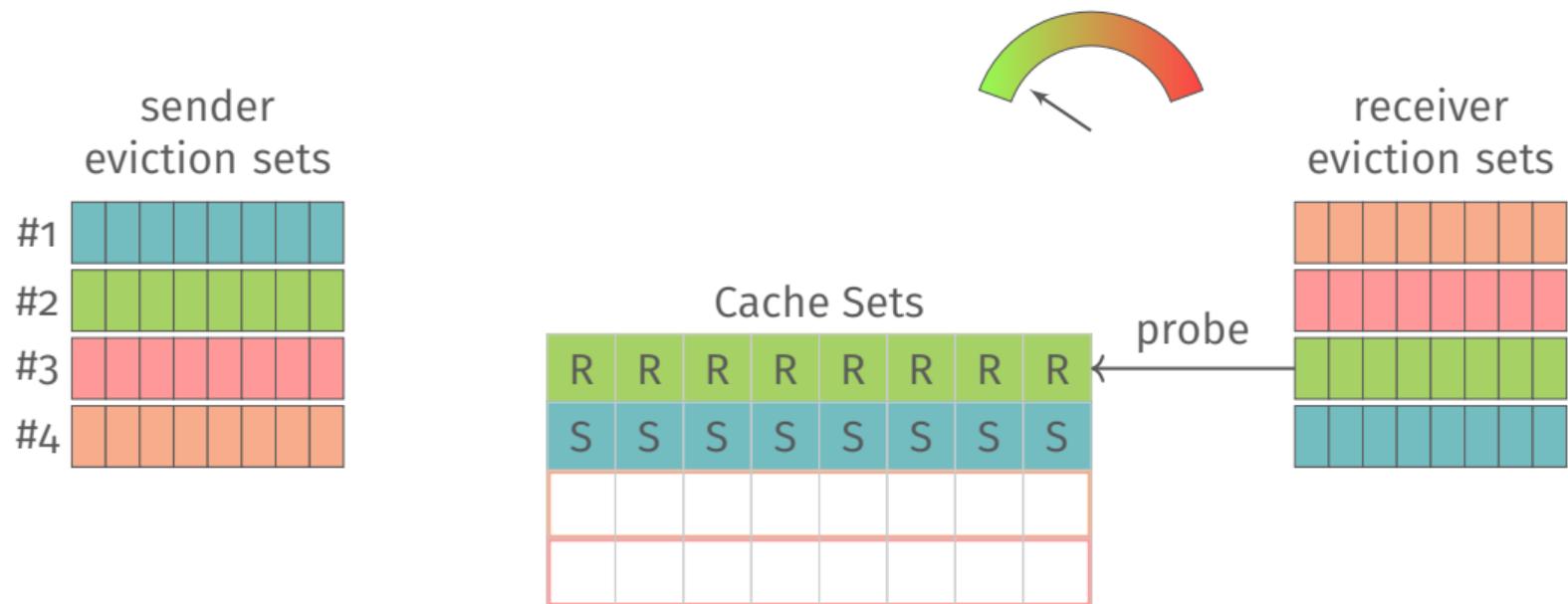
Jamming agreement



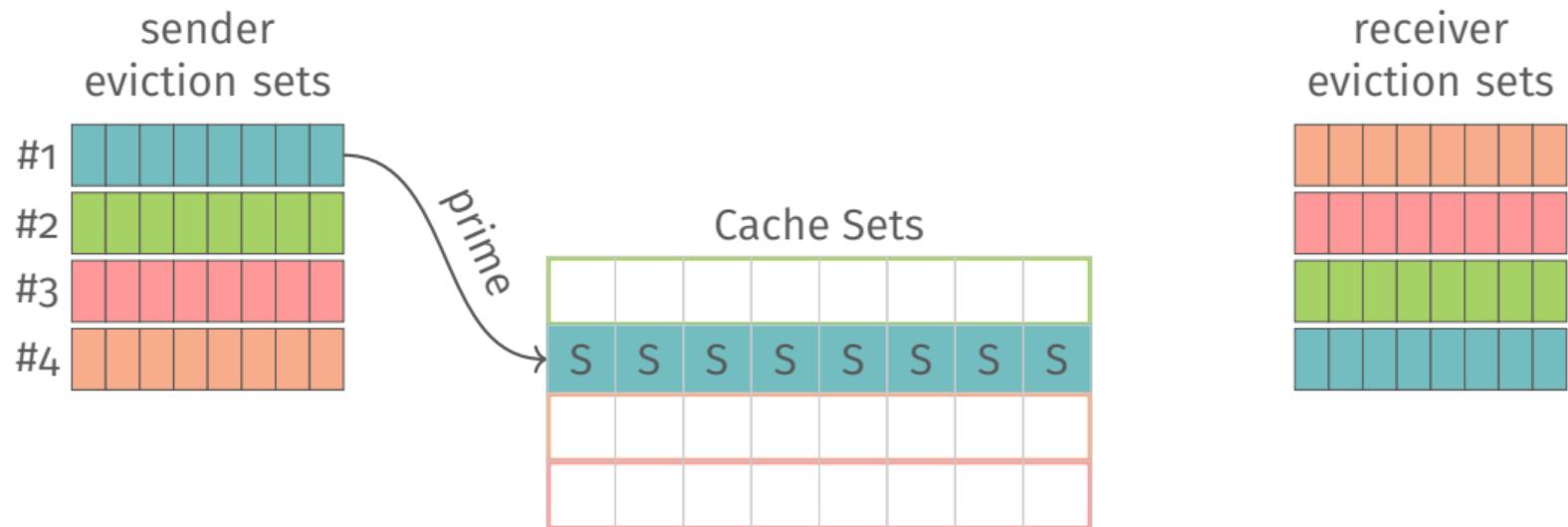
Jamming agreement



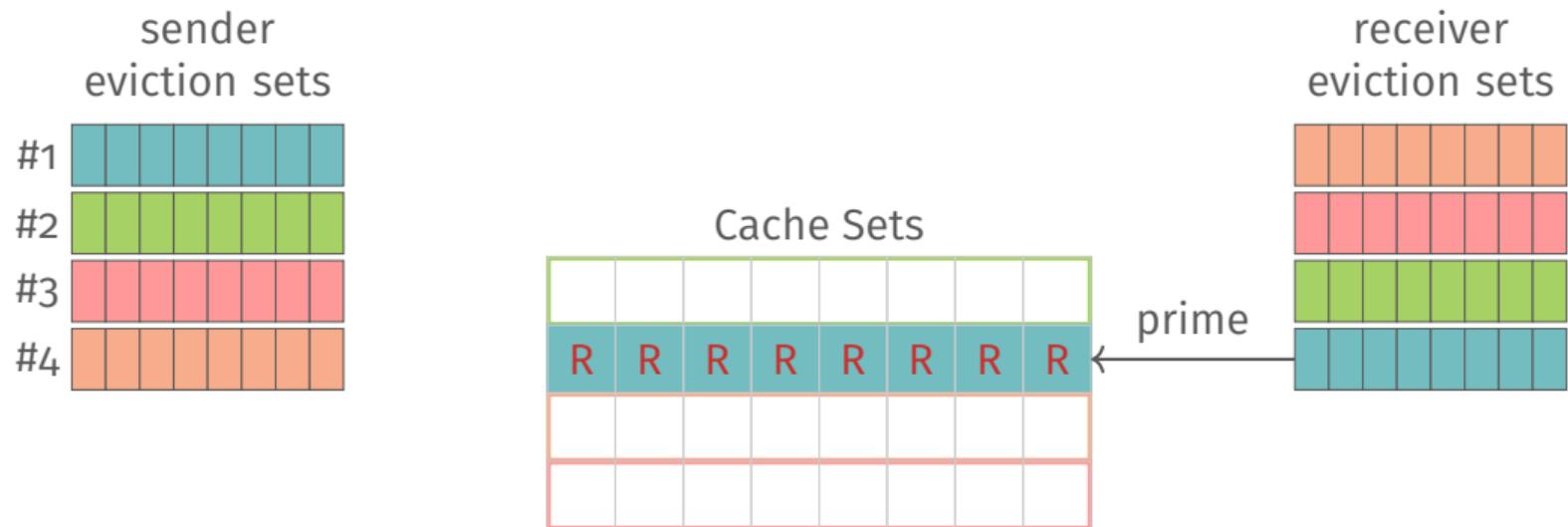
Jamming agreement



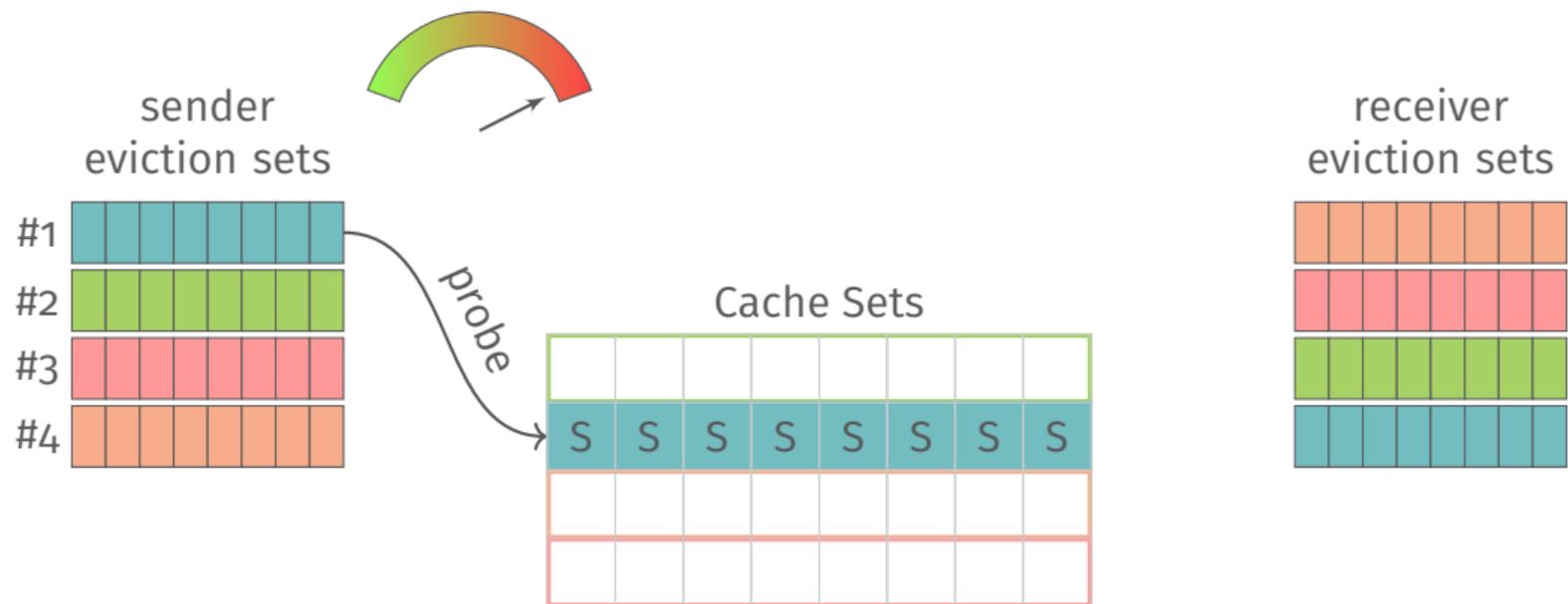
Jamming agreement



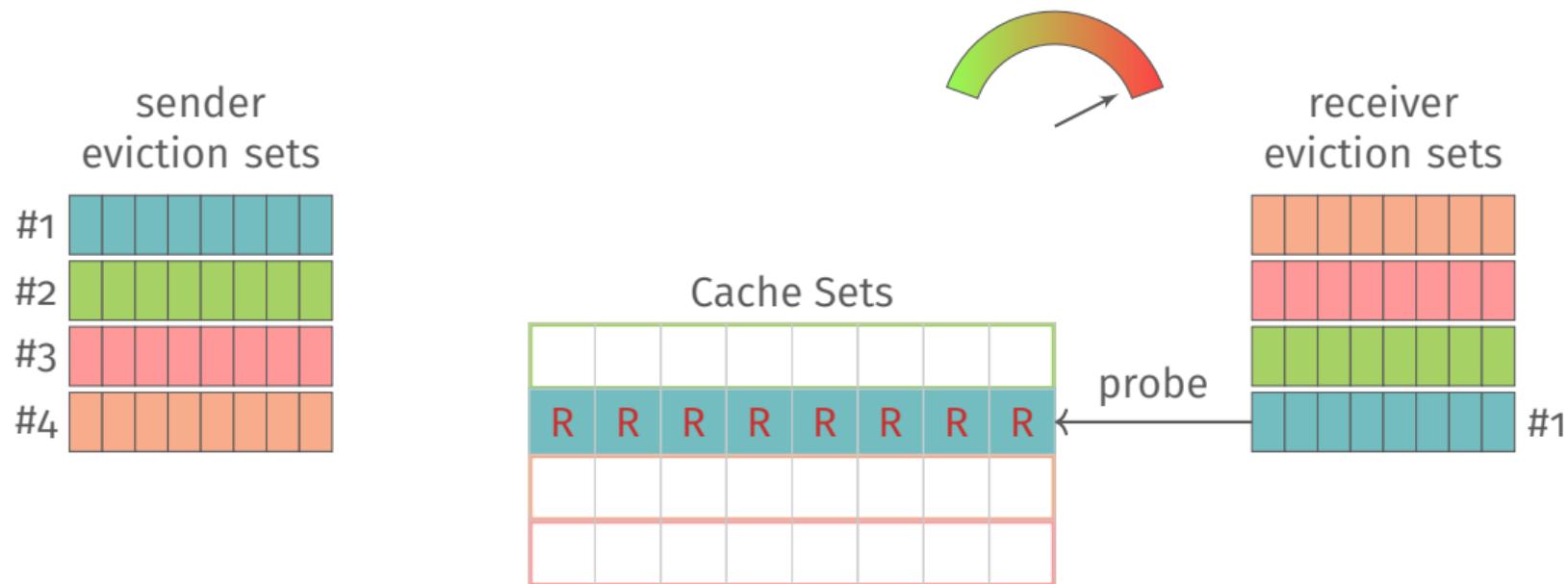
Jamming agreement



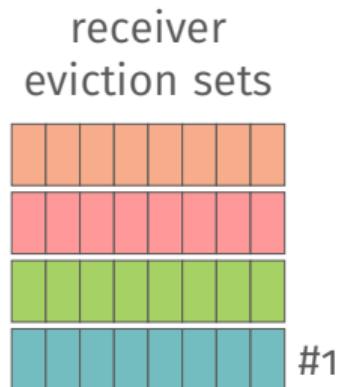
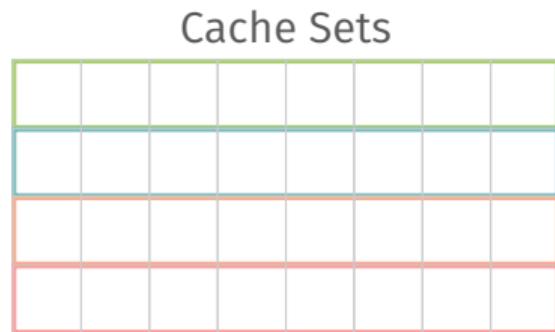
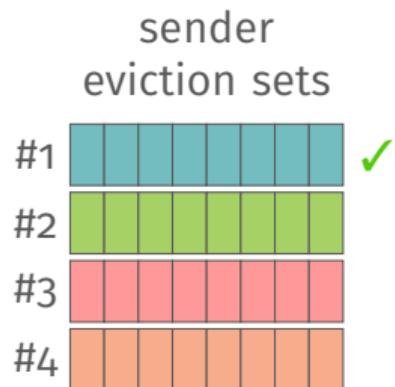
Jamming agreement



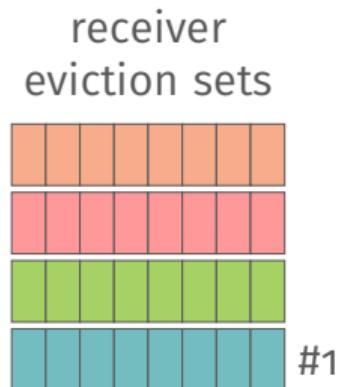
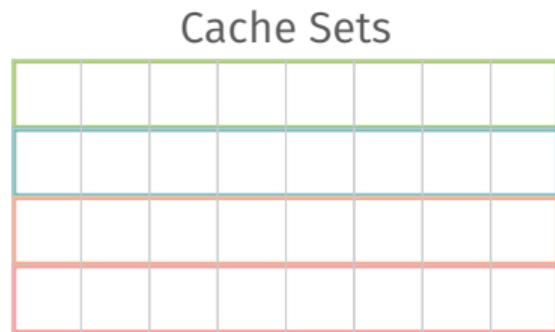
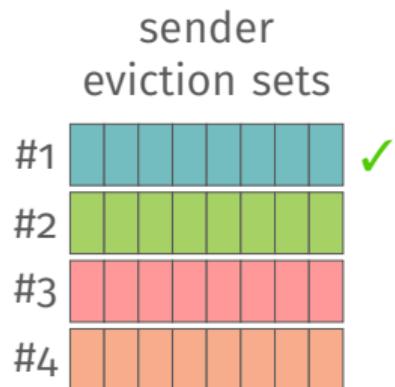
Jamming agreement



Jamming agreement

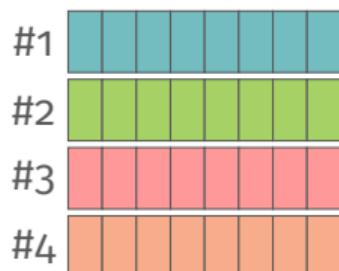


Jamming agreement



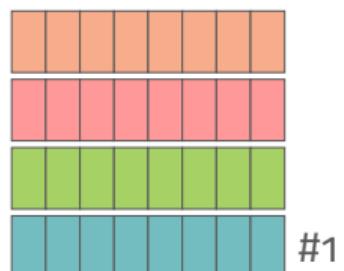
Jamming agreement

sender
eviction sets

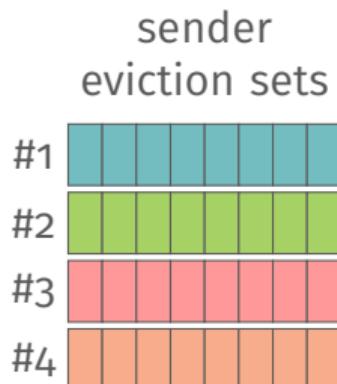


repeat!

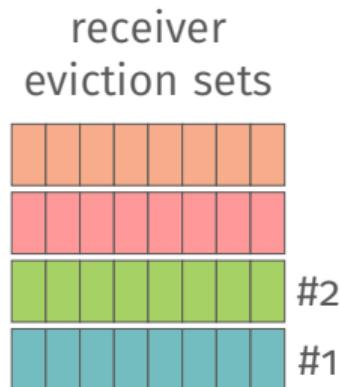
receiver
eviction sets



Jamming agreement

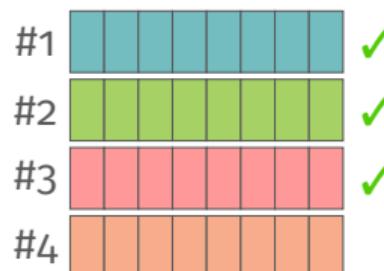


repeat!



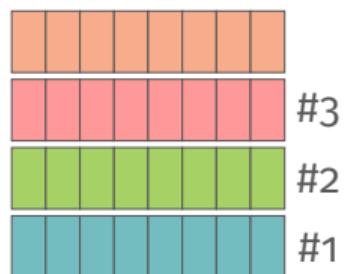
Jamming agreement

sender
eviction sets



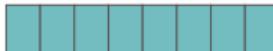
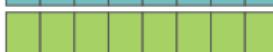
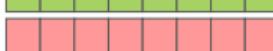
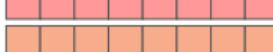
repeat!

receiver
eviction sets



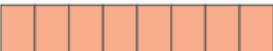
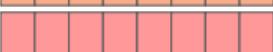
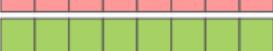
Jamming agreement

sender
eviction sets

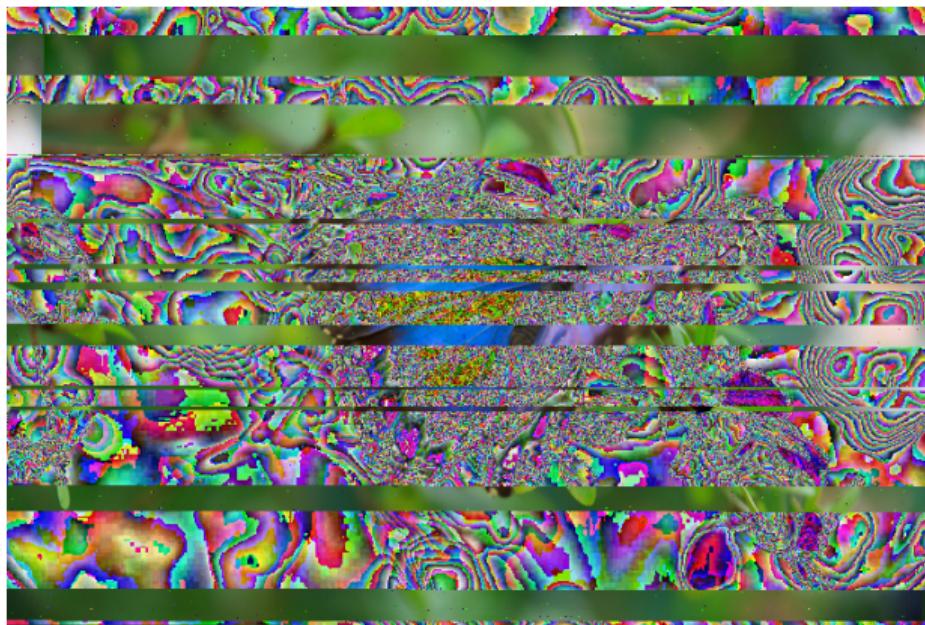
#1		✓
#2		✓
#3		✓
#4		✓

repeat!

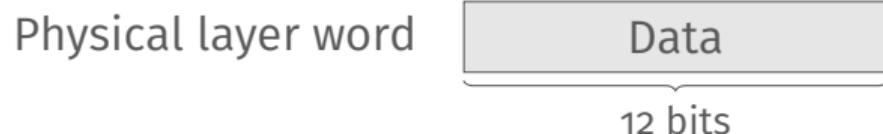
receiver
eviction sets

#4	
#3	
#2	
#1	

Sending the first image



Handling synchronization errors



Handling synchronization errors

- deletion errors: **request-to-send scheme** that also serves as ack
 - 3-bit sequence number
 - request: encoded sequence number (7 bits)

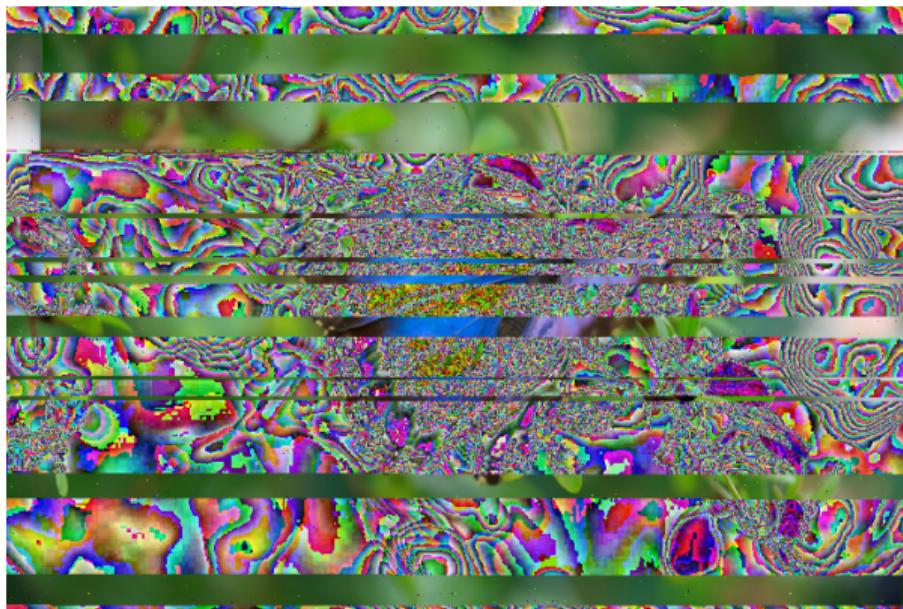


Handling synchronization errors

- deletion errors: **request-to-send scheme** that also serves as ack
 - 3-bit sequence number
 - request: encoded sequence number (7 bits)
- 'o'-insertion errors: **error detection code** → Berger codes
 - appending the number of 'o's in the word to itself
 - property: a word cannot consist solely of 'o's



Synchronization (before)



Synchronization (after)



Synchronization (after)



Synchronization (after)

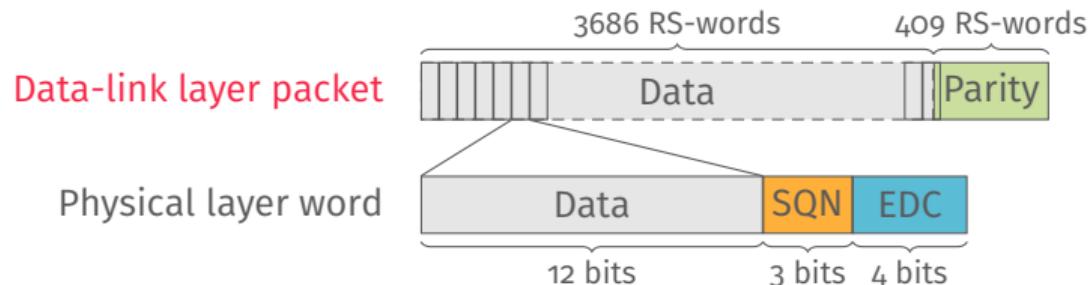


Data-link layer: Error correction

- Reed-Solomon codes to correct the remaining errors

Data-link layer: Error correction

- Reed-Solomon codes to correct the remaining errors
- RS word size = physical layer word size = 12 bits
- packet size = $2^{12} - 1 = 4095$ RS words
- 10% error-correcting code: 409 parity and 3686 data RS words



Error correction (after)



Evaluation

Environment	Bit rate	Error rate	Noise
Native	75.10 KBps	0.00%	-

Evaluation

Environment	Bit rate	Error rate	Noise
Native	75.10 KBps	0.00%	-
Native	36.03 KBps	0.00%	stress -m 1

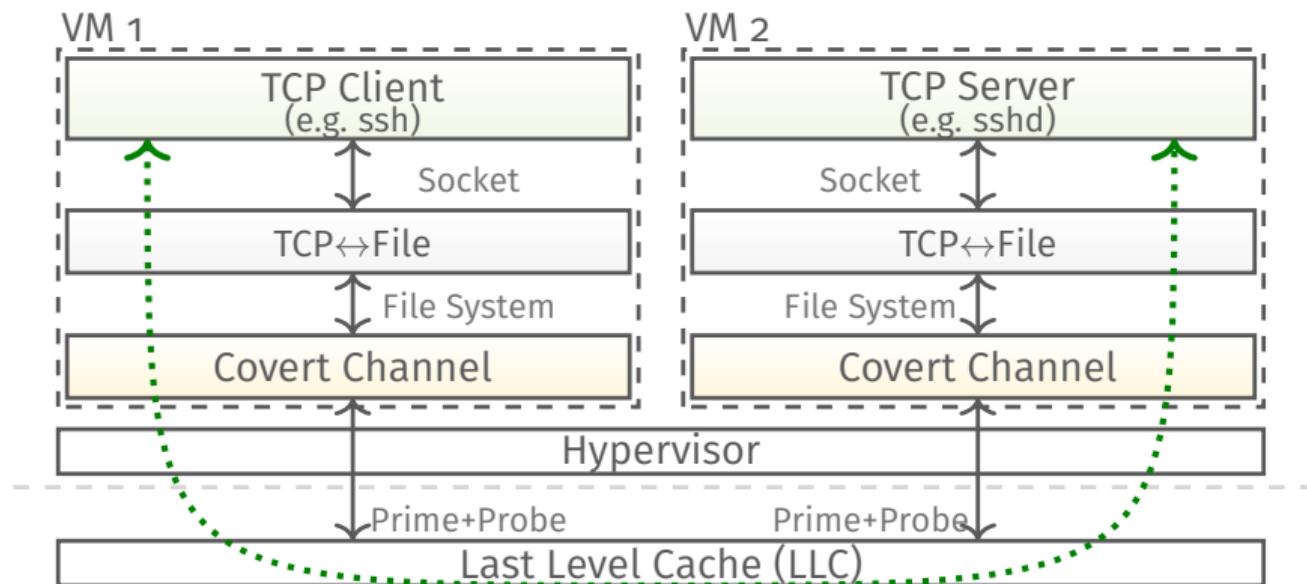
Evaluation

Environment	Bit rate	Error rate	Noise
Native	75.10 KBps	0.00%	-
Native	36.03 KBps	0.00%	stress -m 1
Amazon EC2	45.25 KBps	0.00%	-

Evaluation

Environment	Bit rate	Error rate	Noise
Native	75.10 KBps	0.00%	–
Native	36.03 KBps	0.00%	stress -m 1
Amazon EC2	45.25 KBps	0.00%	–
Amazon EC2	45.09 KBps	0.00%	web server serving files on sender VM
Amazon EC2	42.96 KBps	0.00%	stress -m 2 on sender VM
Amazon EC2	42.26 KBps	0.00%	stress -m 1 on receiver VM
Amazon EC2	37.42 KBps	0.00%	web server on all 3 VMs, stress -m 4 on 3rd VM, stress -m 1 on sender and receiver VMs
Amazon EC2	34.27 KBps	0.00%	stress -m 8 on third VM

Building an SSH connection



SSH evaluation

Between two instances on Amazon EC2

Noise	Connection
No noise	✓
stress -m 8 on third VM	✓
Web server on third VM	✓
Web server on SSH server VM	✓
Web server on all VMs	✓
stress -m 1 on server side	unstable

SSH evaluation

Between two instances on Amazon EC2

Noise	Connection
No noise	✓
stress -m 8 on third VM	✓
Web server on third VM	✓
Web server on SSH server VM	✓
Web server on all VMs	✓
stress -m 1 on server side	unstable

Telnet also works with occasional corrupted bytes with `stress -m 1`

Conclusion

- cache covert channels are **practical**

Conclusion

- cache covert channels are **practical**
- even in the **cloud**, even in presence of extraordinary **noise**

Conclusion

- cache covert channels are **practical**
- even in the **cloud**, even in presence of extraordinary **noise**
- our robust covert channel supports an SSH connection

Conclusion

- cache covert channels are **practical**
- even in the **cloud**, even in presence of extraordinary **noise**
- our robust covert channel supports an SSH connection
- we extended Amazon's product portfolio :)

Conclusion

- cache covert channels are **practical**
- even in the **cloud**, even in presence of extraordinary **noise**
- our robust covert channel supports an SSH connection
- we extended Amazon's product portfolio :)



Conclusion

- cache covert channels are **practical**
- even in the **cloud**, even in presence of extraordinary **noise**
- our robust covert channel supports an SSH connection
- we extended Amazon's product portfolio :)



Hello from the Other Side: SSH over Robust Cache Covert Channels in the Cloud

Clémentine Maurice, Manuel Weber, Michael Schwarz, Lukas Giner, Daniel Gruss, Carlo Alberto Boano, Stefan Mangard, Kay Römer
Graz University of Technology

February 2017 — NDSS 2017